3-D Numerical Simulations of Volcanic Eruption Column Collapse

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During an explosive volcanic eruption, an eruption cloud forms a buoyant eruption column or a pyroclastic flow. We investigated the critical condition that separates these two eruption styles (column collapse condition) by performing a series of three-dimensional numerical simulations. We identified two types of column collapse in the simulations: collapse from a turbulent jet which efficiently entrains ambient air (jet-type collapse) and that from a fountain with a high concentration of ejected materials (fountain-type collapse). Which type of collapse occurs depends on whether the critical mass discharge rate for column collapse (MDR_C) is larger or smaller than that for the generation of fountain (MDR_F) for a given exit velocity. When the magma temperature is relatively low, MDR_C is smaller than MDR_F; therefore, the jet-type column collapse occurs at the transition between a buoyant eruption column and a column collapse. When the magma temperature is high, on the other hand, MDR_C is larger than MDR_F; the column collapse always occurs in the fountain-type regime.

Keywords: volcanic eruption cloud, column collapse condition, pseudo-gas model, turbulent mixing, volcanic hazard

1. Introduction

During explosive volcanic eruptions, a mixture of hot ash (pyroclasts) and volcanic gas is released from the vent into the atmosphere. The mixture generally has an initial density several times larger than atmospheric density at the volcanic vent. As the ejected material entrains ambient air, the density of the mixture decreases because the entrained air expands by heating from the pyroclasts. If the density of the mixture becomes less than the atmospheric density before the eruption cloud loses its upward momentum, a buoyant plume rises to form a plinian eruption column. On the other hand, if the mixture loses its upward momentum before it becomes buoyant, the eruption column collapses to generate a pyroclastic flow. Because the impact and type of volcanic hazards are largely different between these two eruption regimes, the prediction of the condition where an eruption column collapses to generate a pyroclastic flow has been of serious concern; we refer to this condition as "the column collapse condition" [e.g., 1].

Previously, the 1-dimensional (1-D) steady eruption column models [e.g., 2] enabled us to predict column heights and column collapse condition for given magma properties (e.g., water content, n_{g0}, and temperature, T_0) and source conditions (e.g., vent radius, L_0, velocity, w_0, and mass discharge rate, m_0). These models capture the basic physics of column collapse, and their predictions show a quasi-quantitative agreement with field observations of witnessed eruptions [e.g., 3]. Recent works based on the numerical simulations [4] pointed out that the column collapse condition depends on the 2-D and 3-D structures of flow. The flow of a gas-pyroclast mixture near the vent is characterized by a concentric structure consisting of an outer shear region and inner dense core. When the mixture is ejected from a large vent, the outer shear region cannot reach the central axis before the initial momentum is exhausted, so that the inner dense core generates a fountain structure. On the other hand, for the eruption from a relatively narrow vent, the inner dense core disperses due to turbulent mixing and the eruption cloud collapses without a fountain structure.

In this study, we attempt to systematically understand how these 2-D and 3-D effects modify the column collapse condition. For this purpose, we carried out a number of 3-D numerical simulations of eruption cloud with a high spatial resolution. On the basis of an extensive parameter study, we made regime maps of different flow patterns and determined the column collapse condition.

2. Model Description

The simulations are designed to describe the injection of a gas-pyroclasts mixture from a circular vent above a flat surface in a stationary atmosphere with a temperature gradient typical of the mid-latitude atmosphere. The vent is located in the center of the ground surface. The physical domain involves a vertical and horizontal extent of a few kilometers to several tens of kilometers. At the ground boundary, the free-slip condition is assumed for the velocities of the ejected material and air. At the upper and other boundaries of computational domain, the fluxes of mass, momentum, and energy are assumed to be continuous. A gas-pyroclasts mixture with fixed temperature and water content is assumed to erupt at a constant velocity and mass discharge rate at the vent. We assume that the pressure at the vent is same as the atmospheric pressure for simplicity.

We apply a pseudo-gas model; we ignore the separation of solid pyroclasts from the eruption cloud and treat an eruption cloud as a single gas whose density is calculated from mixing ratio of the ejected material and entrained air. The fluid dynamics model solves a set of partial differential equations describing the conservation of mass, momentum, and energy, and constitutive equations describing the thermodynamic state of the mixture of pyroclasts, volcanic gas, and air. These equations are solved numerically by a general scheme for compressible flow. In this study, the calculations are performed on a 3-D domain with a non-uniform grid. The grid size is set to be sufficiently smaller than $L_0/8$ near the vent. Details of the numerical procedures used in this study are described in Suzuki et al. [4].

3. Flow Patterns of Eruption Cloud

In order to capture the characteristics of flow patterns and to determine the column collapse condition, we have performed a parameter study involving about 100 numerical simulations for variable temperature (T_0=550, 800, and 1000 K) and water content (n_{g0}=0.0123 and 0.0284). The mass discharge rate ranges from 10^4 to 10^9 kg s^{-1}. The exit velocity is set to be 0.5a - 3a, where a is the sound velocity of gas-pyroclasts mixture.

The flow patterns in the simulation results are classified into four flow regimes: eruption column with jet structure, eruption column with fountain structure, jet collapse, and fountain collapse. The representative features of each flow regime are described below.

When the mixture is ejected from a narrow vent (L_0=49 m, T_0=1000 K), a stable eruption column develops (Figs. 1a and 1b). The gas-pyroclasts mixuture is ejected from the vent as a dense, high speed jet. After traveling a short distance from the vent, the flow at the boundary between the jet and the ambient air becomes unstable. The jet entrains ambient air by this shear instability: it forms an annular mixing layer which surrounds an unmixed core flow (Fig. 1a). We refer to the mixing layer and the unmixed core flow as "the outer shear layer" and "the inner flow", respectively. The inner flow is eroded by the outer shear layer and disappears at a certain level. As the eruption column further ascends, the flow becomes highly unstable and undergoes a meandering instability that induces efficient mixing. This stream-wise growth of the instabilities results in a complex density distribution in the eruption cloud. Near the vent, the outer shear layer has a lower density than that of air owing to expansion of entrained air, whereas the inner flow remains denser than air (Fig. 1b). After mixing by the meandering instability, the mixture of the ejected material and the entrained air generates a buoyant column. We refer to this flow regime as "the jet-type column".

When the gas-pyroclast mixture is ejected from a large vent (L_0=154 m, T_0=1000 K), the fountain structure develops (Figs. 1c and 1d). Just above the vent, the inner flow is eroded by the outer shear layer (Fig. 1c). In this run, because the vent radius is large, the inner flow reaches the height where the initial momentum is exhausted before the boundary between the inner flow and outer shear layer meets the axis of the flow. The ejected material in the inner flow subsequently spreads radially at this height because of the larger density than that of air (Fig. 1d). Such radially suspended flow is commonly observed in a fountain which results from the injection of a dense fluid upwards into a fluid of lower density. The ejected material is intensively mixed with the ambient air by the large-scale eddy of the radially suspended flow. After the entrainment of ambient air, the resultant mixture becomes buoyant and generates upward flows from the large-scale eddy. We refer to this flow regime as "the fountain-type column".

When the gas-pyroclast mixture is ejected from an extremely large vent (L_0=403 m, T_0=1000 K), the eruption column collapses from a fountain (Figs. 1e and 1f). As the vent radius increases, the ratio of the entrained air against the ejected material decreases, so that the average density of the mixture increases. In this run, the dense part of the ejected material in the fountain collapses to generate pyroclastic flows (Fig. 1f). We refer to this flow regime as "the fountain-type collapse".

In contrast to the fountain-type collapse, when a low-temperature mixture is ejected from a narrow vent (L_0=11 m, T_0=550 K), the eruption column collapses from a jet (Figs. 1g and 1h). In this run, the jet entrains ambient air by the shear instability; the inner flow disappears at a height of 0.5 km (Fig. 1g). The mixture of the ejected material and the entrained air continues rising up to ~1.0 km and falls down to generate a pyroclastic flow because it has a larger density than that of air (Fig. 1f). As the temperature of the ejected material is lower, the larger amount of air should be entrained for eruption cloud to become buoyant. In this run, the eruption cloud remains heavier than air even though it entrains a large amount of air. We refer to this flow regime as "the jet-type collapse".

4. Flow Regime Maps

On the basis of the parameter studies, we made new flow regime maps (Fig. 2). When the magma temperature is relatively low (T_0=550 K), three flow regimes are identified: the jet-type column, the jet-type collapse, and the fountain-type collapse regimes (Fig. 2a). When the magma temperature is high (T_0=1000 K), on the other hand, the possible flow regimes are the jet-type column, the fountain-type column, and the fountain-type collapse regimes (Fig. 2b).

The variation in the flow regime map suggests that two

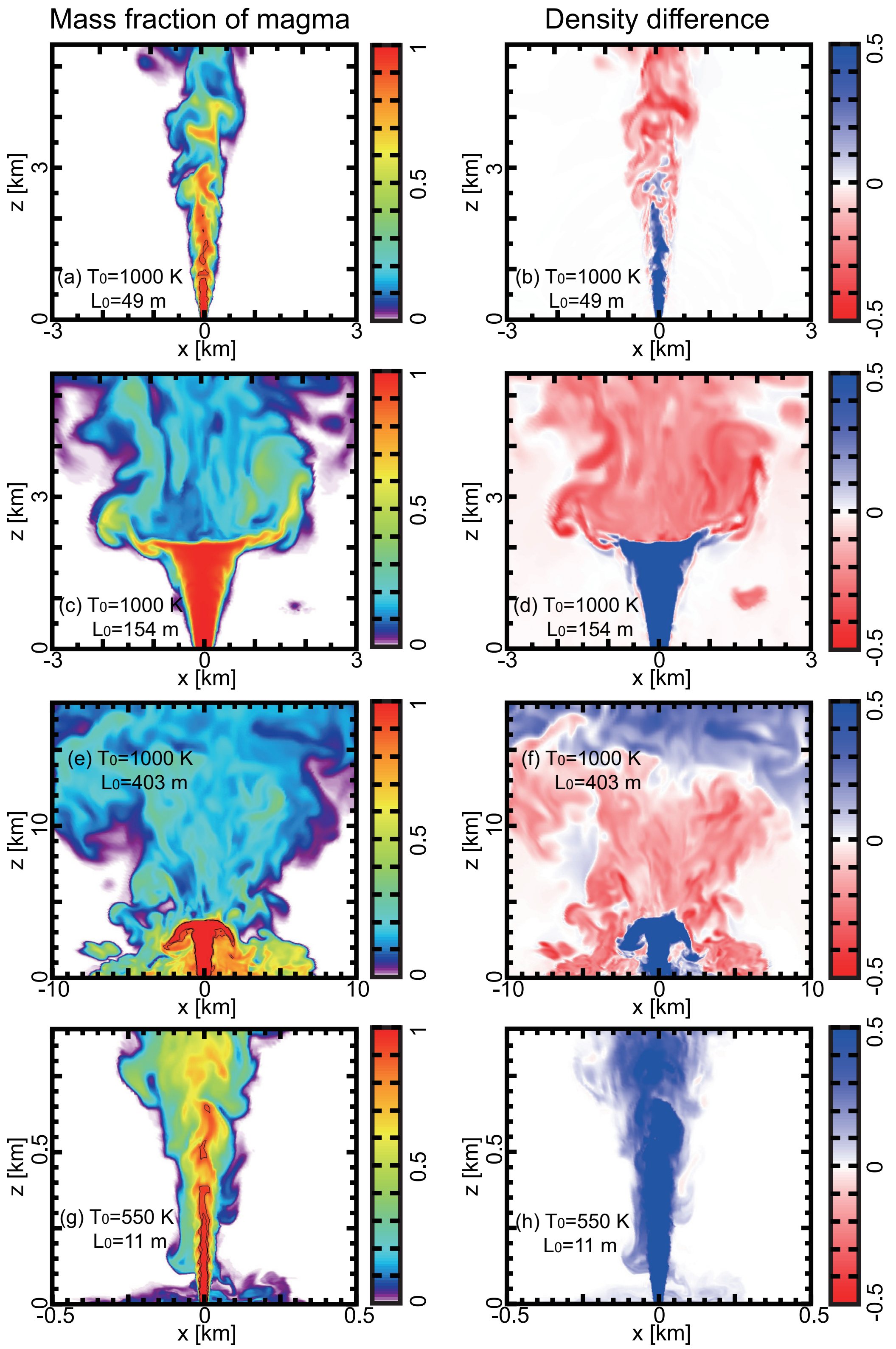

Fig. 1 Numerical results of the gas-pyroclasts mixture ejected from the volcanic vent. Figures (a), (c), (e) and (g) illustrate the cross-sectional distributions of the mass fraction of the ejected material in *x* - *z* space. Figures (b), (d), (f) and (h) illustrate the cross-sectional distributions of the density difference relative to the stratified atmospheric density at the same vertical position, $-\Delta\rho/\rho_a = 1 - \rho/\rho_a$, in *x* - *z* space. (a, b) The jet-type column at 600 s after the beginning of the eruption (m_0=1x10^7 kg s^{-1}, L_0=49 m, w_0=173 m s^{-1}, T_0=1000 K, n_{g0}=0.0284). (c, d) The fountain-type column at 190 s (m_0=1x10^8 kg s^{-1}, L_0=154 m, w_0=173 m s^{-1}, T_0=1000 K, n_{g0}=0.0284). (e, f) The fountain-type collapse at 500 s (m_0=1x10^9 kg s^{-1}, L_0=403 m, w_0=254 m s^{-1}, T_0=1000 K, n_{g0}=0.0284). (g, h) The jet-type collapse at 120 s (m_0=1x10^6 kg s^{-1}, L_0=11 m, w_0=179 m s^{-1}, T_0=550 K, n_{g0}=0.0284).

critical conditions control the transition of the flow regimes: the column collapse condition (solid curves) and the critical condition for the generation of fountain (dashed curves). When the temperature is relatively low, the critical mass discharge rate for the column collapse (MDR_C) is smaller than that for the generation of fountain (MDR_F) for a given exit velocity (Fig. 2a). In this case, the column collapse occurs in the jet-type and fountain-type regimes. The flow pattern at the column collapse condition is characterized by the jet-type collapse. As the exit velocity increases, MDR_C increases with a slope similar to that predicted by the 1-D model (see solid and dotted curves in Fig. 2a). When the temperature is high, on the other hand, MDR_C is larger than MDR_F. In this case, the column collapse always occurs in the fountain-type regime (Fig. 2b). The column collapse condition for the fountain-type regime is largely different from that predicted by the 1-D model; the increase rate of MDR_C based on the 3-D simulations is larger than that based on the 1-D model (see solid and dotted curves in Fig. 2b).

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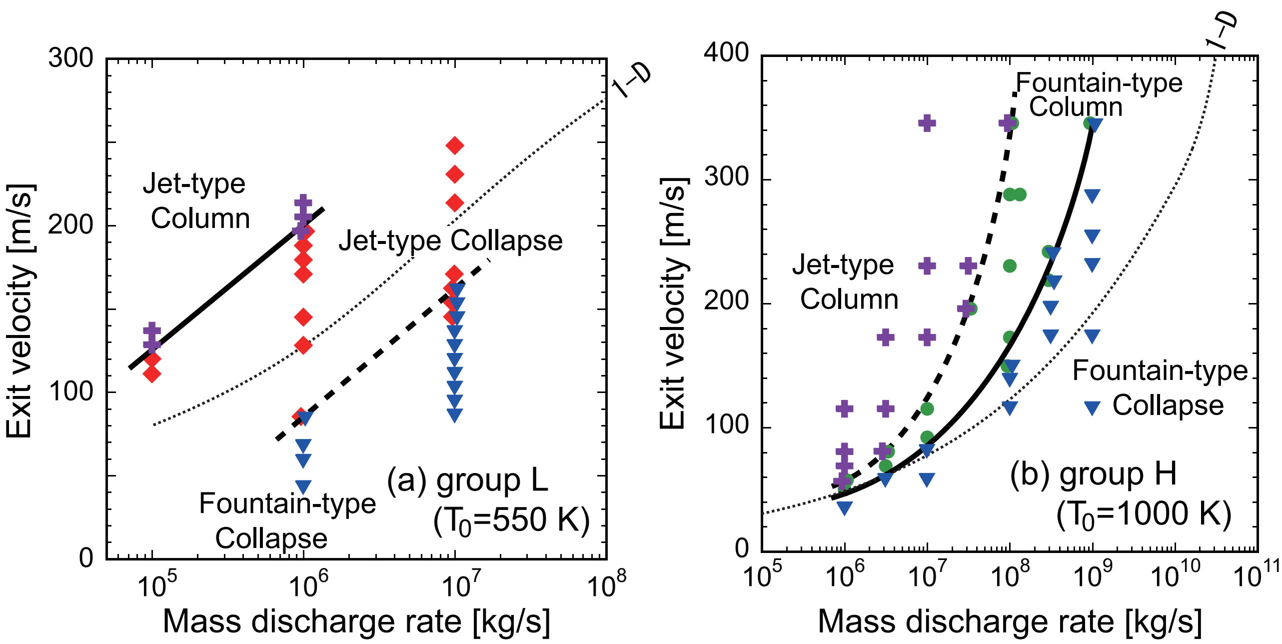

Fig. 2 Flow regime maps for (a) the low temperature case: group L, and (b) the high temperature case: group H. Purple pluses represent the jet-type column regime. Red diamonds are the jet-type collapse regime. Blue triangles represent the fountain-type collapse regime. Green circles indicate the fountain-type column regime. Solid curves are the column collapse condition. Dashed curves are the critical condition for the generation of fountain. Dotted curves illustrate the column collapse condition predicted by the previous 1-D model.

3 次元数値シミュレーションによる噴煙柱崩壊条件の解析

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本プロジェクトでは、大規模数値シミュレーションを用いた固体地球と地球表層・大気にまたがる火山現象の理解と計算結果の防災への応用を目指している。本年は特に、火山噴煙における火砕流発生条件について研究を進めた。

爆発的火山噴火では、噴煙柱と火砕流という二つの特徴的な噴火スタイルが見られる。火山ガスと火砕物からなる噴出物は、固体である火砕物を含むために火口では大気よりも重い状態にある。しかし、噴煙と大気の境界で乱流によって周囲大気を取り込むと、火砕物の熱によって取り込んだ大気を急激に膨張させ、噴煙密度は低下する。噴煙が火口での初期運動量を失う高さに達する前に噴煙密度が大気密度よりも小さくなれば、浮力を獲得して噴煙柱となる。一方、噴煙密度が大気密度より大きいまま初期運動量を失ってしまうと、浮力は得られずに火砕流となる。これら二つのレジームの境界が噴煙柱崩壊条件であり、これまでは 1 次元定常噴煙モデル（例えば、Woods, 1988）に基づいた予測がされてきた。しかし、その予測は野外観察や室内実験から見積もられる噴煙柱崩壊条件とのズレが指摘されてきた。火砕流発生条件を正確に予測することは火山学上のみならず防災上も非常に重要である。本研究では、3 次元噴煙モデル（Suzuki et al.,2005）によるシミュレーションを行い、噴煙柱崩壊条件を求めた。

数値計算の結果、Jet-type と Fountain-type の 2 つの噴煙柱崩壊のタイプが存在することが分かった。火口から出た噴煙は、大気との境界で生じるせん断流れによって大気と混合する。その混合層は火口から離れるにしたがって中心軸に向かって成長するため、中心軸付近に存在するポテンシャルコアと呼ばれる周囲大気と混合していない領域は縮小していく。したがって、火口半径が大きいほどポテンシャルコアの長さは増大する。火口半径が大きいと、初期運動量を失う高さでせん断流れが中心軸付近まで達せず、ポテンシャルコアが残る。この時、ポテンシャルコアの重い噴煙は水平方向に広がって Fountain 構造を形成しつつ火砕流を発生させる（Fountain-type collapse）。一方、火口半径が小さいと、初期運動量を失う前にせん断流れが中心軸付近まで達し、ポテンシャルコアは消滅する。この時、噴煙が重い状態にあれば、ジェットのような構造をもった噴煙柱崩壊となる（Jet-type collapse）。

噴出速度が与えられた時、噴出率もしくは火口半径が増大すると、噴煙柱から噴煙柱崩壊への遷移、及び、Jet-type から Fountain-type への遷移が起こる。ここに、それぞれの遷移に対する臨界噴出率を MDR_C 及び MDR_F と呼ぶことにする。パラメータスタディに基づくレジームマップを作成すると、噴煙柱崩壊条件の時に Jet-type と Fountain-type のいずれの噴煙柱崩壊となるかは、MDR_C と MDR_F の大小関係に依存することが分かった。マグマ温度の低い噴火では MDR_C が MDR_F よりも小さく、噴煙柱崩壊条件で Jet-type collapse が発生する。一方、温度の高いマグマ噴火では MDR_C が MDR_F よりも大きく、噴煙柱崩壊条件で Fountain-type collapse が発生する。この場合、火砕流発生条件は 1 次元定常モデルの予想から大きくずれ、火砕流が発生しやすいことが分かった。

キーワード: 火山噴煙 , 火砕流 , 擬似ガスモデル , 乱流混合 , 火山災害